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Evaluating the effects of seismic loading on concrete reinforced versus precast concrete slab floor systems

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EVALUATING THE EFFECTS OF SEISMIC LOADING ON CONCRETE REINFORCED VERSUS PRECAST CONCRETE SLAB FLOOR SYSTEMS

By

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A thesis submitted to the faculty of The University of Mississippi in partial fulfillment of the requirements of the Sally McDonnell Barksdale Honors College.

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DEDICATION

This thesis is dedicated to everyone who has helped me throughout my undergraduate degree, especially my grandparents, Mr. Ganesh Bahadur Maharjan, Mrs. Heramaya Devi Maharjan, and Mrs. Anar Keshari Singh.

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Lastly, I would like to thank my family, especially my mom and dad for their infinite support and love. I would haven't been able to complete this work without their encouragement and unending motivation.

ABSTRACT

This thesis is part of the senior design capstone project of Ole Miss Department of Civil Engineering. The seismic loadings for the commercial buildings project located in Oxford, Mississippi are evaluated to fulfill the honor thesis requirement. This thesis follows the codes from American Concrete Institute (ACI), International Building Code (IBC), and ASCE-7/SEI (Minimum Design Loads and Associated Criteria for Buildings and Other Structures/Structural Engineering Institute) to design the gravitational loadings and seismic loadings.

Furthermore, a reinforced concrete slab flooring system is replaced with a precast slab flooring system to analyze the most seismic performance effective floor system for the building. Both structural systems are analyzed using SAP 2000. Also, a cost analysis is executed to estimate the price difference and to select suitable flooring systems.

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LIST OF ABBREVIATIONS

ε_t net tensile strain in an extreme layer of longitudinal tension reinforcement

Φ safety factor for beam bending design, a value equal to 0.9 for a 10% reduction

ρ steel fraction percentage of the concrete area

ACI American Concrete Institute

AISC American Institute of Steel Construction

A_s the required area of steel bar in square inches

b width of the beam

C_s seismic response coefficient

C_{vx} vertical distribution factor

d depth of the beam

DL Dead Load

F_a short period site coefficient (at 0.2 second period) [ASCE-7 Table 11.4.1]

f_c' specified compressive strength of the concrete

F_v long-period site coefficient at 1 second period [ASCE-7 Table 11.4.2]

F_x lateral seismic load for each floor in kips

f_x lateral seismic load for each floor in kips/feet

f_y yield strength or stress

h height of the beam

HC Hollow core

h_s height of the slab

h_x height of the structure from the base

HVAC Heating, Ventilation, and Air conditioning

IBC International Building Code

I_e Seismic Importance factor

LC Load Cases

LL Live Load

LRFD Load and Resistance Factor Design

MCE_R Risk targeted maximum considered earthquake

M_u Ultimate moment

PC Precast Concrete

PCI Prestressed/Precast Concrete Institute

psf pounds per square foot

S_1 Spectral response accelerations at 1 second period

S_s Spectral response accelerations at short periods

S_{D1} 5 percent damped design spectral response accelerations at 1 second period

S_{DS} 5 percent damped design spectral response accelerations at short periods

RC Reinforced Concrete

USGS United States Geological Survey

V seismic base shear

w_x weight of each floor

w_s self-weight of the one-way solid slab in pounds per square foot

Chapter 1: Introduction

A part of the senior design capstone tasks for the civil engineering senior students was designing and analyzing a commercial building project. The project is located at Sisk Avenue, Oxford, Mississippi with the latitude and longitude of 34°22'21.7"N and 89°29'48.1"W. The civil engineering capstone project consisted of six main design and analysis tasks i.e. site planning, analyzing subsurface exploration, analyzing and designing the structural system, foundation, and stormwater systems. The emphasis is on the structural analysis and design part of the capstone project.

The main focus of the structural loading part was to analyze the loadings for the building so that the structural members can be designed based on that. For the honor thesis, the objective was to investigate the lateral loading effects especially from the earthquake loadings generated due to the location of the building. Moreover, two slab systems were studied to evaluate the seismic loadings on the structural system response.

1.1 Project overview

The design project consisted of two buildings located in consecutive plots at Oxford Commons, Mississippi. Each plot has an area of 1.17 acres and will have a two-story building. The Sisk Avenue is in the north, Commonwealth Blvd on East, Enterprise Drive on West, and the Hopkins Drive on South of the project location shown in Figure 1.1.

Figure 1. 1: Project Location on Sisk Avenue [11]

1.2 Project Outline

The students were tasked to select the floor plans and functionality of the buildings. Based on the Oxford Ordinance and city regulations, the layout of the building is selected as presented in Figure 1.2 [17]. Each building has dimensions of 120’×98’.

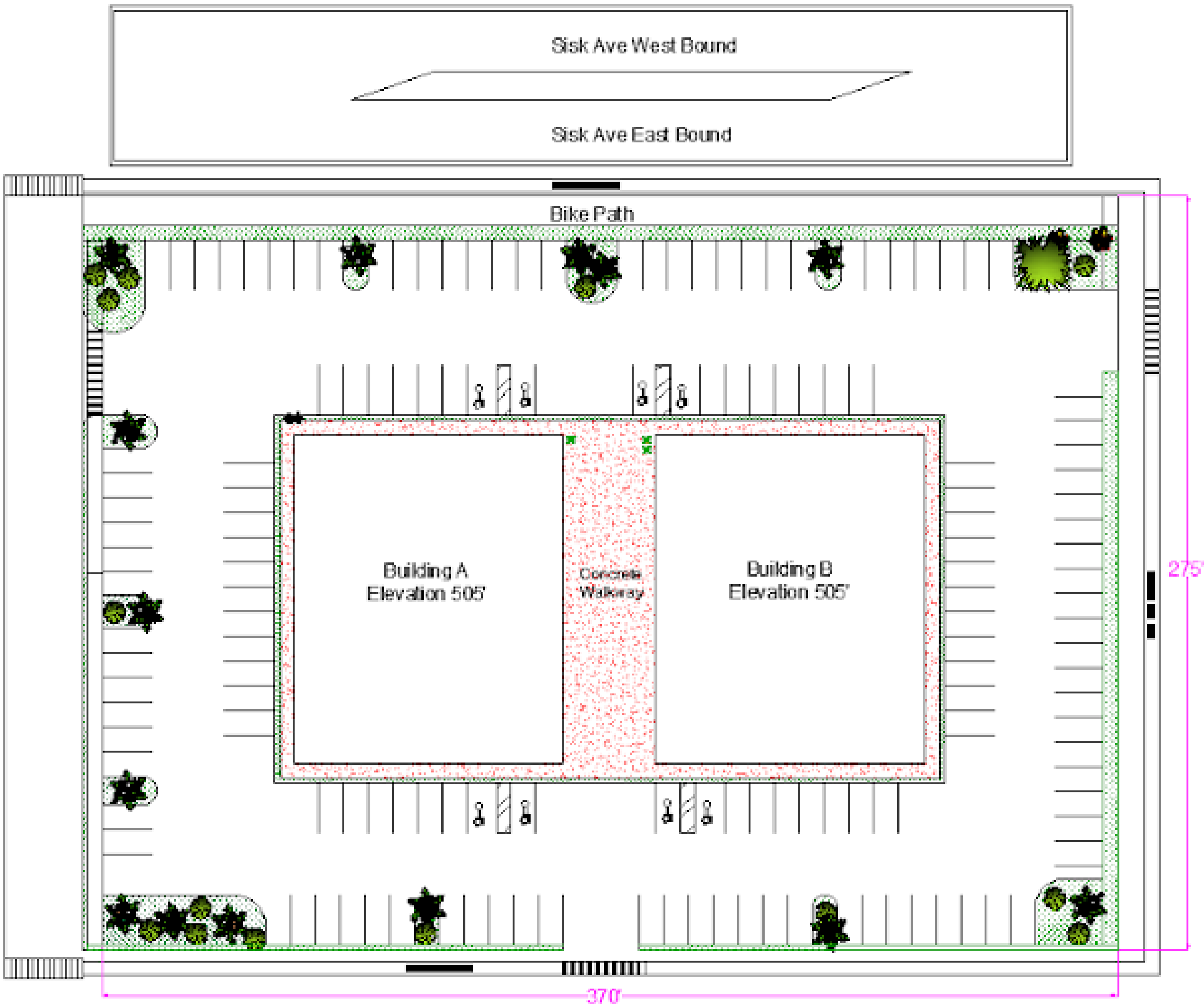


Figure 1. 2: Overall Plan view of the project

As shown in Figure 1.3, Building A's first floor is a Trader Joe’s store and the second floor is for dental care and offices. On the other hand, Building B consists of offices, a smoothie king, gym, vitamin shop, and pet store.

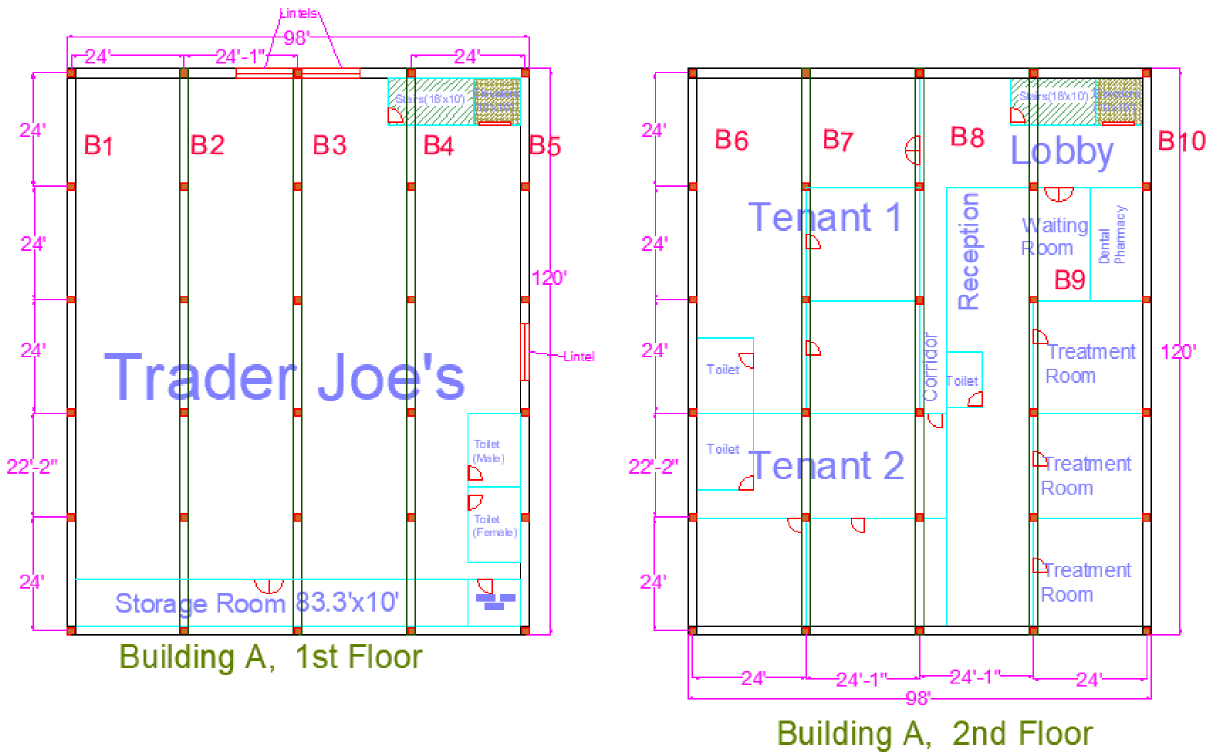


Figure 1. 3: Floor Outline for Building A [5]

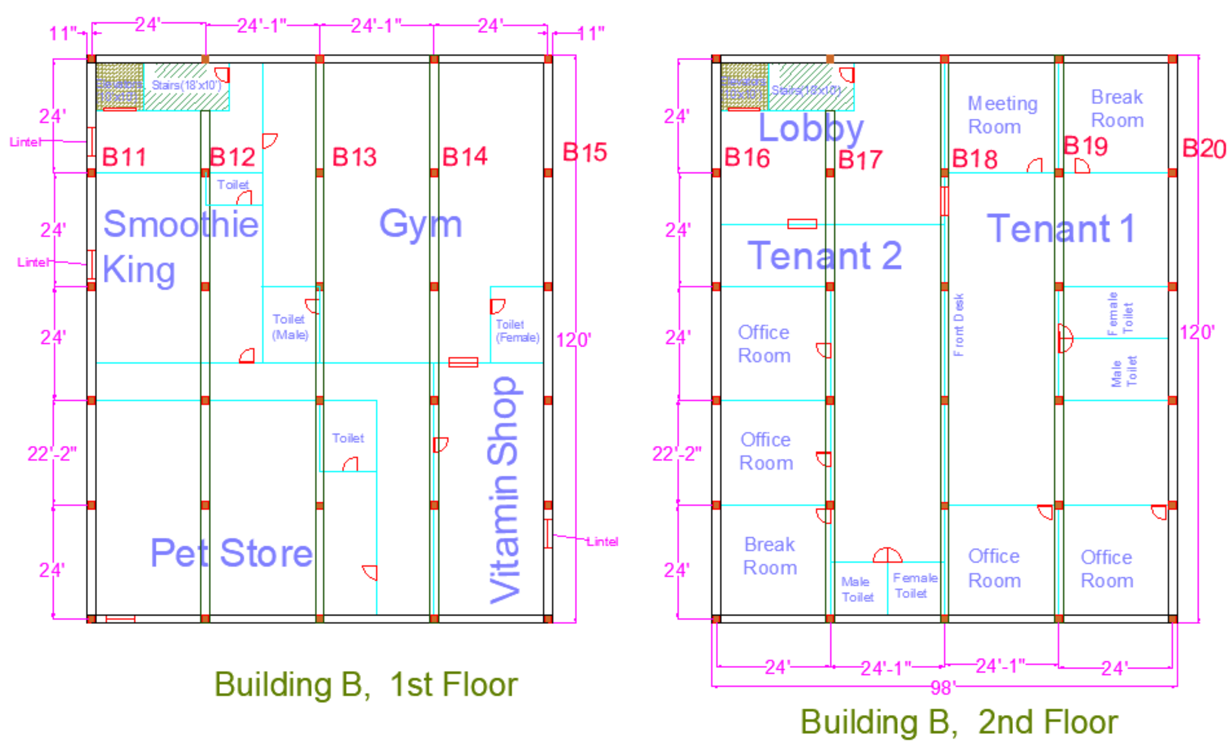
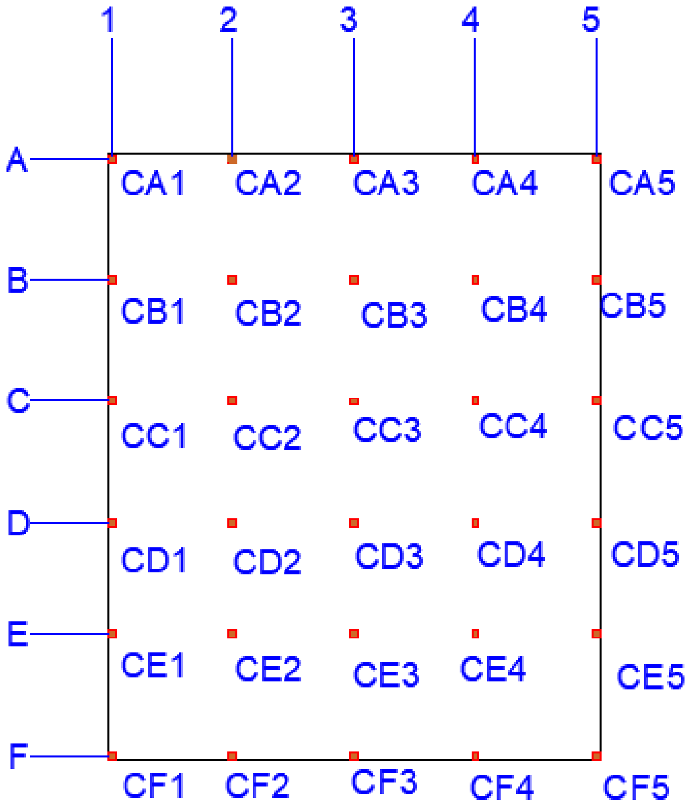
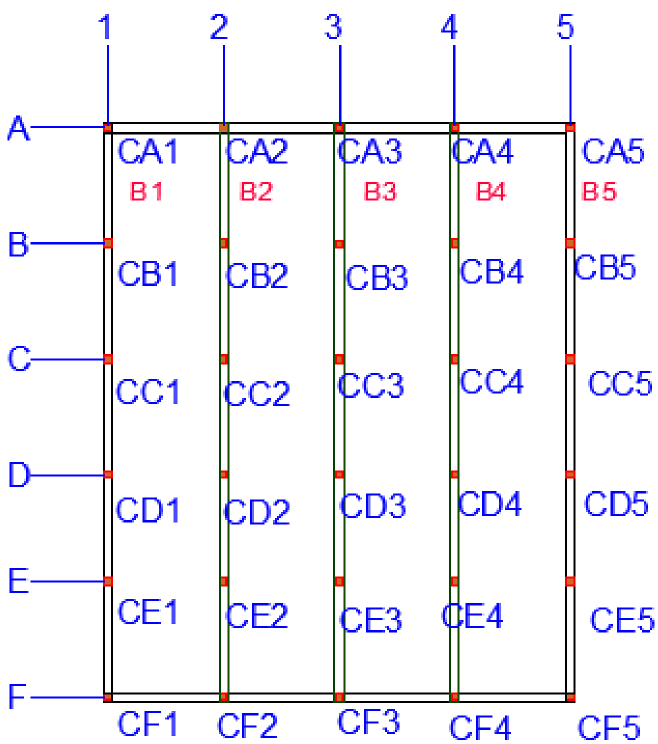


Figure 1. 4: Floor Outline for Building B [5]



Building A, 1st floor



Building A, 2nd Floor

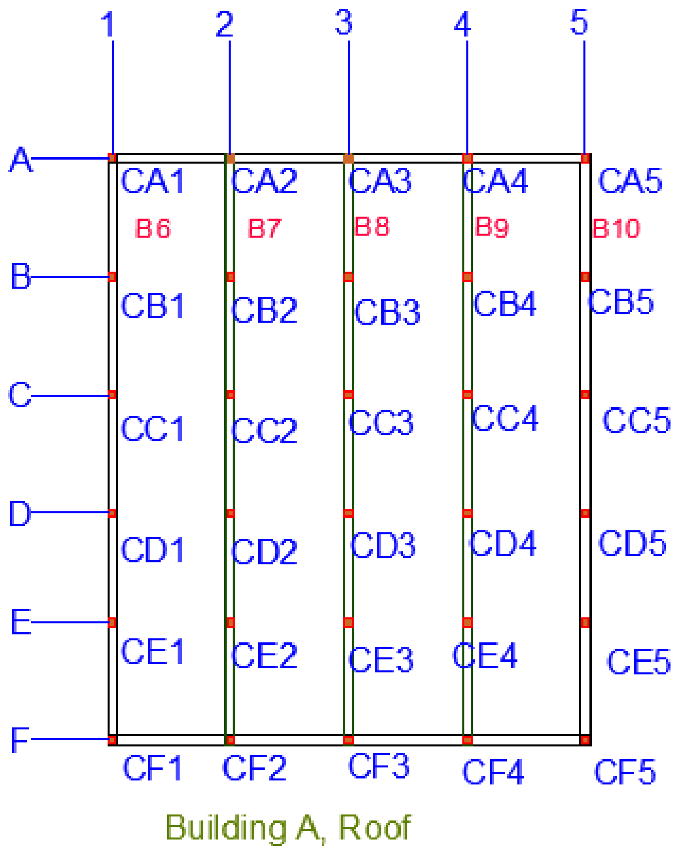


Figure 1. 5: Structural floor Plan for Building A [5]

1.3 Structural Load

Structural Load is the total amount of forces or the loads carried by the building including its self-weight. These loads can cause deformation, stress, and displacements of the building or the structural members of the building [21]. It is essential to determine the structural load applied to a building to ensure structural stability and this helps to predict the various modes of failure in case of different scenarios. The structure must be designed in a way to withstand the various loads during its service life.

There are various types of loads generated in the building based on the selected construction materials, structural system, and location of the building [21]. Some of the major applied loads are given below:

1. Dead load: A dead load of a structure generated from beams, slabs, and columns. In other words, the dead load is the total non-dynamic structural load of the system. It is a load that depends on the materials used for the construction like concrete, timber, or steel.
2. Superimposed dead load: Superimposed dead loads depends on periodic occupancy of the structure. These loads are semi-dynamic and can rotate around different areas of the structure. Some of the sources of the dead load include floor finish, window/frames, electrical wiring, stairs, elevators, HVAC ductwork, and plumbing.
3. Live loads: Live loads result from dynamic forces due to occupancy and functionality of the structure. They represent the transient forces that can be moved through the building or act on any particular structural element. Some of the sources of live loads are the weight of people, furniture, appliances, and automobiles including other moveable equipment.
4. Environmental loads: The external dynamic loads resulting from natural activities like snow, wind, rain, soil movement, or earthquake (seismic) activity. It mainly depends on the geographical and topographic conditions.

Chapter 2: Reinforced Concrete Slab System

Reinforced Concrete is a composite material made up of steel bars and concrete. Concrete is the mixture of cement, water, and aggregates (sand and gravel) that hardens over time. It is the second most-consumed material on the earth. Besides the steel rebar in the concrete is mostly made of recycled steel which makes it a sustainable product.

In reinforced concrete, steel bars provide tensile strength i.e. strength to resist pull force, and concrete provides compressive strength i.e. strength to resist compression. It is a durable, aesthetically pleasing, and fire-resistant material used in construction.

2.1 Gravitational Load Calculation

2.1.1 Dead Load

Estimating the slab self-weight

According to American Concrete Institute (ACI) code 7.3.1.1 and 9.3.1.1, the minimum thickness in one way slab with the deflection criteria is shown in Figure 2.1.

Table 2.4 – Minimum Thickness / Depth of One-way Slabs and Beams

Member	Support Condition	Minimum Thickness, h
One-way slab	One end continuous	$\ell/24$
	Both ends continuous	$\ell/28$
	Cantilever	$\ell/10$
Beam	One end continuous	$\ell/18.5$
	Both ends continuous	$\ell/21$
	Cantilever	$\ell/8$

1. For f_y other than 60,000 psi, multiply the tabulated expressions by $0.4 + f_y/100{,}000$ where f_y is in psi.
2. For concrete having w_c in the range of 90 to 115 lb/ft^3, multiply tabulated expressions by the larger of (a) $1.65 - 0.005w_c$ or (b) 1.09.

Figure 2. 1: Minimum Thickness of one-way slabs. [10]

For the solid one-way slab with one end continuous, the minimum thickness of the slab

$$(h_s) = \frac{Span\ Length\ (L)}{24} = \frac{24ft}{24} * \frac{12\ in}{1ft} = 12\ inches = 1\ feet$$

$$Self\ weight\ of\ slab\ (ws) = \ Density\ of\ concrete\ x\ height\ of\ slab$$

$$= 150\frac{lb}{ft^3} \times 1\ ft = 150psf$$

2.1.2 Estimating Superimposed Dead Load

The superimposed load of the building is determined through the American Institute of Steel Construction (AISC). As shown in Table 2.1, the superimposed load for the first floor is 58.5 psf and the roof is 7 psf.

Table 2. 1: Superimposed Load Calculations

	Structural component	**Load (psf)**
For the first floor	Floor Finish(Hardwood, 7/8 in)	4
	Window (glass, frame and)	8
	Partition (Drywall, 5/8 in)	2.5
	Mechanical Duct	4
	Piping (8in diameter)	40
[redacted]		**58.5**
For roof	Roof finish (wood, 3/4 in)	3
	Mechanical Duct	4
	[redacted]	**7**

2.1.3 Estimating Live Load

The live load of the building is determined through International Building Code (IBC-2016) and Table 2.2 summarizes the live load for the structure based on occupancy.

Table 2. 2: Live Load based on the occupancy of the building [12]

Floor	Functionality/Occupancy	Live Load (psf)
First floor	**Trader Joe's shopping area**	**125**
	Mechanical Room and storage	**100**
Second floor	Lobby, corridor offices	100
	Dental care	60
Roof	General roof live load	20

2.2 Estimating Environmental Load

The environmental load is mainly considered based on the weather and location of the city. The environmental load considered for Oxford, MS is summarized in Table 2.3.

Table 2. 3: Environmental Load for Oxford, MS

Environmental Load	Load (psf)
Rain Load	20
Snow Load	10

To analyze the difference between various loading conditions on the structural member, a moment frame system from Building A is selected as presented in Figure 2.2. A moment frame is a special type frame that uses rigid connections between its members [2]. This arrangement resists lateral and overturning forces induced by bending moment and shear forces [7]. Because of the building symmetry, the analysis of a moment frame can represent the whole system when applied lateral earthquake load.

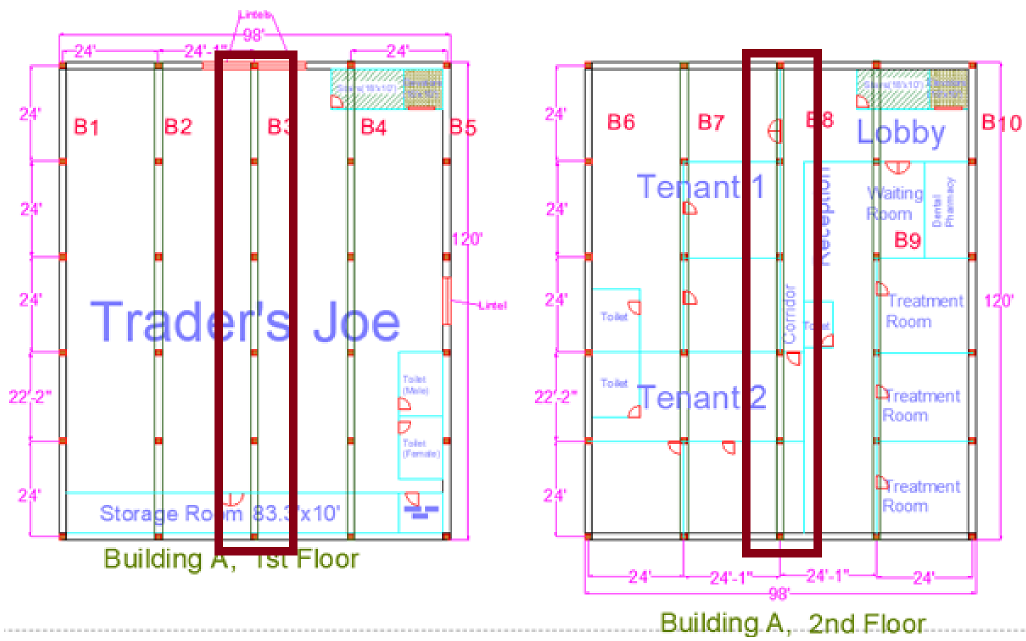


Figure 2. 2: Selected section for the moment frame of Building A

2.3 Combined Load Effect

The load factors and combinations used in the reinforced concrete are presented in ACI 318 5.3. This is further verified in ASCE/SEI-7 and IBC. The selected method is known as Load and Resistance Factor Design (LRFD). Following the codes, the various load cases are evaluated and the most critical combination is selected.

The following equations are analyzed to determine the most critical factored combined load applied to the building [13].

LC1: $U = 1.4D$ (ACI Equation 5.3.1a)

LC2: $U = 1.2D + 1.6L + 0.5(L_r \text{ or } S \text{ or } R)$ (ACI Equation 5.3.1b)

LC3: $U = 1.2D + 1.6(L_r \text{ or } S \text{ or } R) + (L \text{ or } 0.5W)$ (ACI Equation 5.3.1c)

LC4: $U = 1.2D + 1.0W + L + 0.5(L_r \text{ or } S \text{ or } R)$ (ACI Equation 5.3.1d)

LC5: $U = 1.2D + 1.0E + L + 0.2S$ (ACI Equation 5.3.1e)

LC6: $U = 0.9D + 1.0W$ (ACI Equation 5.3.1f)

LC7: $U = 0.9D + 1.0E$ (ACI Equation 5.3.1g)

Where U = ultimate load of the structure needs to resist

D = Dead Load L = Live Load

L_r = Roof Live Load S = Snow Load

R = Rain Load W = Wind Load

E = Seismic or Earthquake Load effects

All these load cases are investigated to determine the maximum loading cases. The load case 2 was the maximum for the gravity load cases. However, when the seismic load was considered the LC 5 was maximum for the roof and LC 2 was maximum for the first floor as shown in Appendix A Figures A.2 and A.3.

SAP 2000 analysis was performed to determine the bending moment on the moment-resisting frame based on LC 2 [9]. All the calculations are performed in Excel shown in the figures in Appendix A.

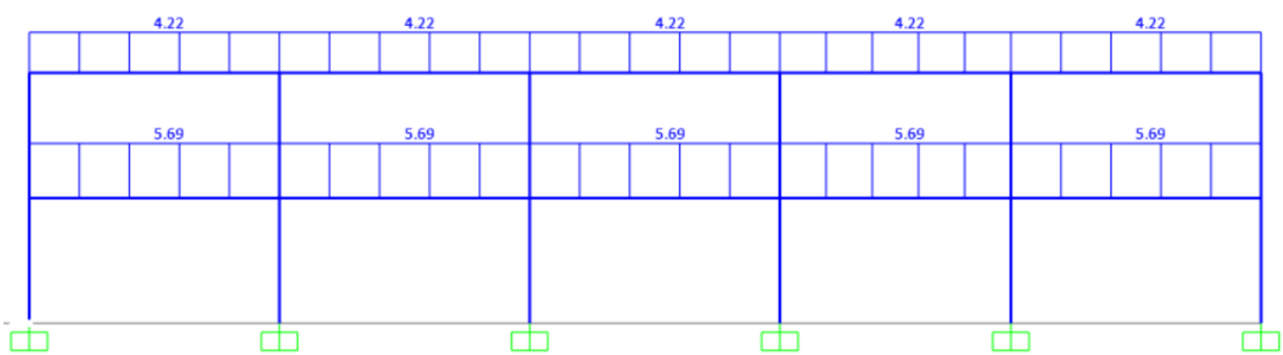


Figure 2. 3: Total dead load applied to the moment frame.

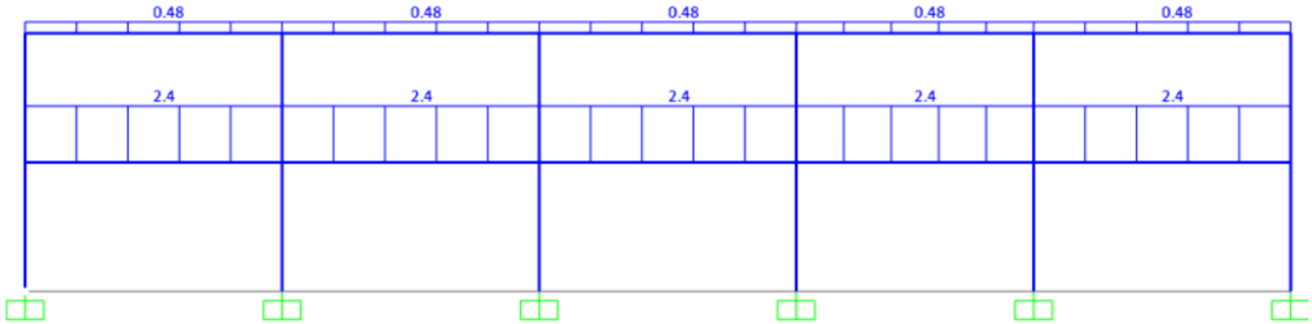


Figure 2. 4: Total live load applied to the moment frame.

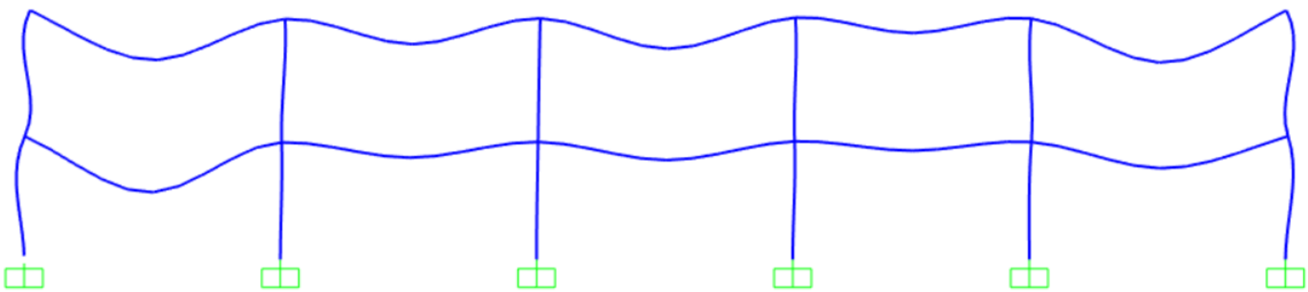


Figure 2. 5: Deflection under the influence of live and dead load (LC2)

Chapter 3: Seismic Load Estimation for RC slab

The seismic loading is the response of the structure to earthquake oscillation. It depends on various parameters like geotechnical parameters, the seismic location of the site, and the building's natural frequency. The seismic force has both horizontal and vertical components [24]. However, the horizontal forces mainly cause the failure so only horizontal forces are mainly considered for the design.

Earthquake generally occurs along the boundary of a plane because of moving crustal plates which are thousands of feet below the earth's surface. The nearest boundary plane is approximately 1700 kilometers south of Mississippi near the coast of Honduras, where the North American and Caribbean plates join [20]. Oxford lies within the vicinity of the New Madrid Seismic Zone that can result in moderate seismic activity as shown in Figure 3.1 below.

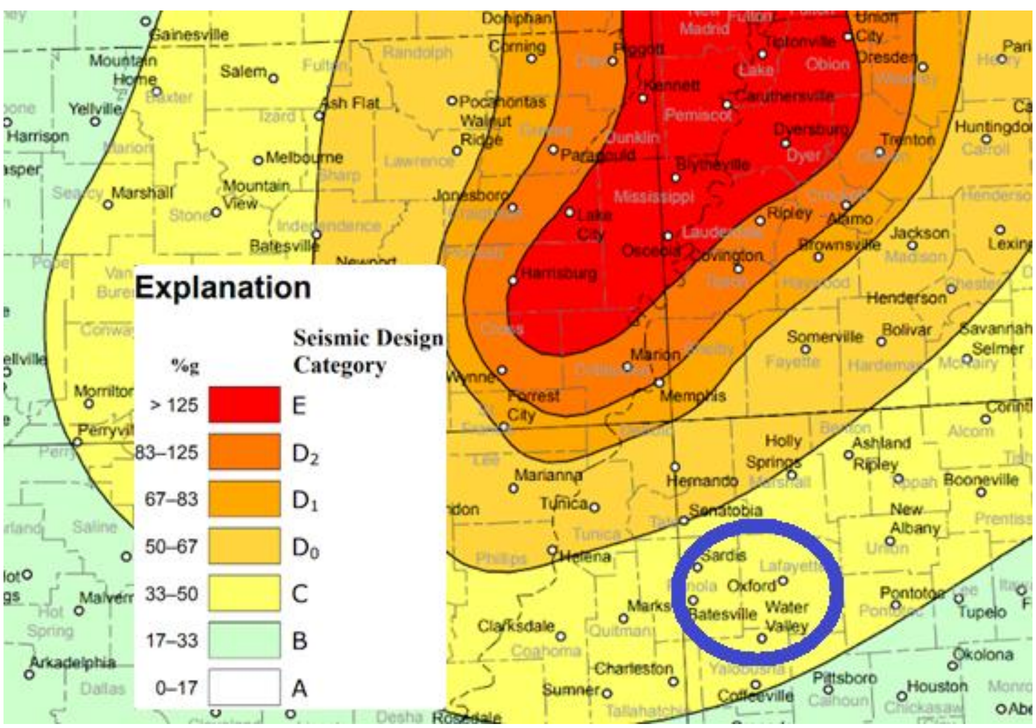


Figure 3. 1: Earthquake Zone for the Oxford, Mississippi [22]

Similarly, the same moment frame of Building A is analyzed for the seismic loading. As the building is symmetrical, the analysis of a moment frame can represent the whole system when earthquake load is applied.

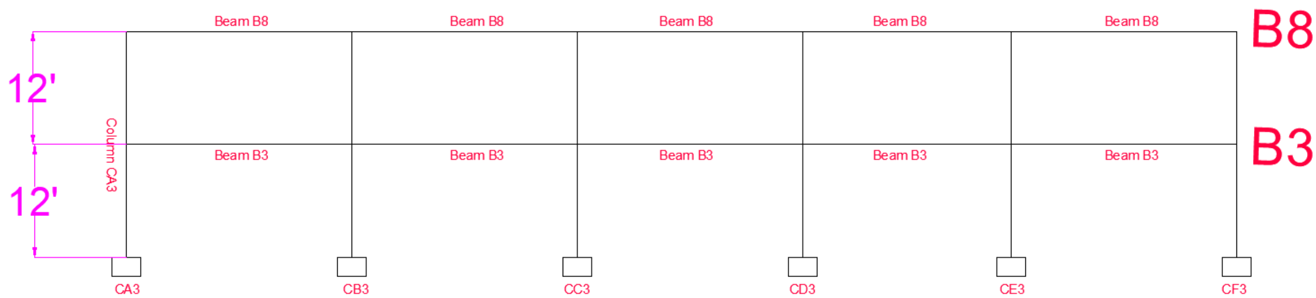


Figure 3. 2: Moment frame for B3 and B8

3.1 Estimation for the seismic loading.

The seismic loading is determined using a seismic code master designed under the 2015 International Building Code (IBC) and ASCE/SEI 7-10 [8]. The multistep calculation processes followed to determine the earthquake loading is shown below.

Step 1: Determining spectral response accelerations for risk-targeted maximum considered earthquake (MCE_R)

The values for the spectral response accelerations at short periods (S_s) and at 1-second period (S_1) is determined following the United States Geological Survey (USGS). The latitude/longitude for the location is provided on the ASCE-7 hazard tool and the output is delivered as shown in Figure 3.3.

ASCE
AMERICAN SOCIETY OF CIVIL ENGINEERS

Seismic

Site Soil Class: C - Very Dense Soil and Soft Rock

Results:

S_S :	0.416	S_{D1} :	0.179
S_1 :	0.179	T_L :	12
F_a :	1.3	PGA :	0.218
F_v :	1.5	PGA_M :	0.261
S_{MS} :	0.54	F_{PGA} :	1.2
S_{M1} :	0.268	I_e :	1.25
S_{DS} :	0.36	C_v :	0.877

Seismic Design Category C

Figure 3. 3: ASCE Hazard Tool Output for Oxford, MS [4]

From Figure 3.3, S_s=0.416, S_1=0.179

Step 2: Determine if the structure is exempt from the seismic requirements.

The city of Oxford, Mississippi lies in the moderate seismic zone so it is not exempted from the seismic requirements.

Step 3: Structural Design Category (SDC)

The soil is classified as Class C soil in accordance with ASCE 7-10 and 2015 IBC for Oxford, MS.

To determine the design spectral response acceleration, short period and long period coefficient (F_a and F_v) are required. Following Table 11.4.1 and 11.4.2 from ASCE-7 and for soil type C as shown in Figure C.1

F_a=1.3 F_v =1.5

$$S_{DS} = \frac{2}{3}F_aS_s = \frac{2}{3}(1.3)(0.416) = 0.361$$

$$S_{D1} = \frac{2}{3}F_vS_1 = \frac{2}{3}(1.5)(0.179) = 0.179$$

Determining the risk category:

The building is a public space with more than 300 people so Risk Category III is selected.

Table 3. 1: Determination of risk category based on 2015 IBC-1604.

Risk Category	Nature of Occupancy
I	Risk Category I is assigned to agricultural facilities, temporary facilities, and minor storage facilities that represent a low hazard to human life in the event of failure.
II	Risk Category II is assigned to most structures; it is assigned to structures not otherwise classified as Risk Category I, III, or IV.
III	Risk Category III is for structures with large numbers of persons such as: • Schools with more than 250 students. • Assembly uses with more than 300 people, and • Structures with total occupancy greater than 5000 people. Risk Category III is also assigned to:] • Nonessential utility facilities and • Jails and detention facilities.

IV	Risk Category IV includes hospitals and acute care facilities; fire, police, and emergency response stations; aviation control towers; and utilizes required for essential facilities.

Step 4: Determine responsive modification coefficient (R)

R is the rating for and ability of a structural system to resist earthquake ground motion without collapse. The R is determined from ASCE 7 Table 12.2-1 for the moment-resisting frame system. The equivalent lateral force method is selected for the analysis procedure of seismic loadings.

Table 12.2-1 (*Continued*)

Seismic Force-Resisting System	ASCE 7 Section Where Detailing Requirements Are Specified	Response Modification Coefficient, R[a]	Overstrength Factor, Ω_0[g]	Deflection Amplification Factor, C_d[b]	Structural System Limitations Including Structural Height, h_n (ft) Limits[c] — Seismic Design Category: B	C	D[d]	E[d]	F[e]
C. MOMENT-RESISTING FRAME SYSTEMS									
1. Steel special moment frames	14.1 and 12.2.5.5	8	3	5½	NL	NL	NL	NL	NL
2. Steel special truss moment frames	14.1	7	3	5½	NL	NL	160	100	NP
3. Steel intermediate moment frames	12.2.5.7 and 14.1	4½	3	4	NL	NL	35[h]	NP[h]	NP[h]
4. Steel ordinary moment frames	12.2.5.6 and 14.1	3½	3	3	NL	NL	NP[i]	NP[i]	NP[i]
5. Special reinforced concrete moment frames[n]	12.2.5.5 and 14.2	8	3	5½	NL	NL	NL	NL	NL
6. Intermediate reinforced concrete moment frames	14.2	5	3	4½	NL	NL	NP	NP	NP
7. Ordinary reinforced concrete moment frames	14.2	3	3	2½	NL	NP	NP	NP	NP
8. Steel and concrete composite special moment frames	12.2.5.5 and 14.3	8	3	5½	NL	NL	NL	NL	NL
9. Steel and concrete composite intermediate moment frames	14.3	5	3	4½	NL	NL	NP	NP	NP

Figure 3. 4: Design Coefficients and Factors for Seismic Force-Resisting Systems [3]

So, R for ordinary reinforced concrete moment frames =3

Step 5: Determine seismic importance factor (I_e):

It is the seismic performance capabilities of structures in various risk categories. It modifies the design base shear depending on the occupancy during the earthquake event. For risk category III, $I_e = 1.25$ which increases the design shear base by 25%.

Step 6: Determine seismic base shear (V): The base shear is calculated using the following equations,

$$V = C_s W$$

Where C_s= seismic response coefficient $= \frac{S_{DS}}{R/I_e}$

W=weight of the building = 2185.4 kips [From excel calculations]

$$C_s = \frac{S_{DS}}{R/I_e} = \frac{0.36}{3/1.25} = 0.15$$

$$V = C_s W = 0.15 \times 1592 = 239 kips$$

Step 7: Distribute V over the height of the structure.

ASCE7-10 section 12.8.3 corresponds to design base shear distributed over the height of the structure.

$$F_x = C_{vx} V$$

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k}$$

For the first floor

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k} = \frac{971 * 12}{26564.4} = 0.44$$

$$F_x = 0.44 * 239 = \frac{104.92k}{120ft} = 0.87k/ft$$

Table 3. 2: Distribution of shear over the height of the structure

Floor	**h_x (ft)**	**w_x (k)**	**$w_x h_x$ (kft)**	**C_{vx}**	**F_x (k)**	**f_x (k/ft)**
First	12	971.0	11652	0.44	104.92	0.87
Roof	24	621.4	14913	0.56	134.28	1.12
		$\Sigma w_i h_i$	26564.4			

Step 8: Determine Redundancy Factor, *ρ*

According to ASCE 7-10 Section 12.3.4, for Seismic Design Category A, B, or C structures, the redundancy factor is taken as 1. This simply means that the redundancy factor does not apply.

Step 10: Load combinations

The earthquake effects are combined with the effects of gravity loads according to 2015 IBC Section 1605. The calculation is shown in Figure

$$\mathrm{LC1: U = (1.2 + 0.2S_{DS})D + f_1L + f_2S + \rho Q_E}$$

$$\mathrm{LC2: U = (0.9 - 0.2S_{DS})D + \rho Q_E}$$

Table 3. 3: Critical Loading Combinations with without seismic and with seismic case [1]

Load Combination	**Beam B3 (k/ft)**	**Beam B8 (k/ft)**
U = 1.2D + 1.6L + 0.5(L_r or S or R)	10.67	6.07
$\mathbf{U = (1.2 + 0.2S_{DS})D + f_1L + f_2S + \rho Q_E}$	10.51	7.44

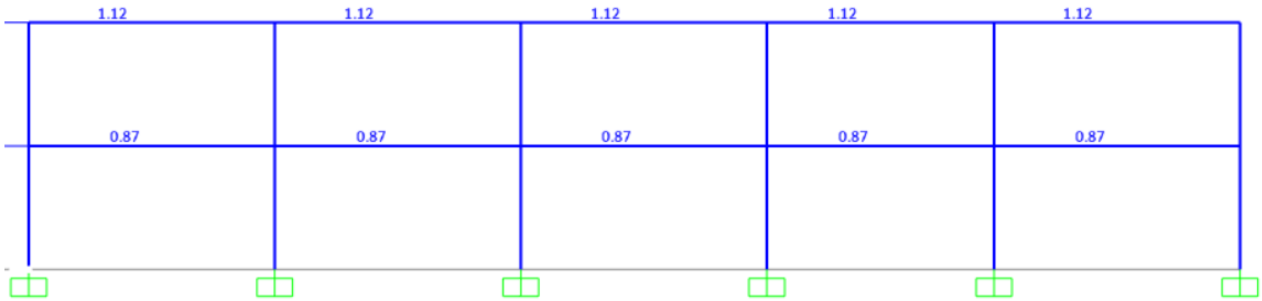


Figure 3. 5: Seismic load applied to the moment frame.

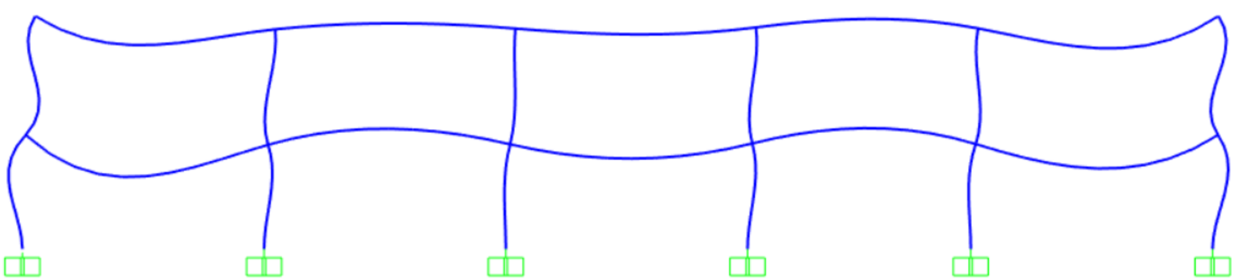


Figure 3. 6: Deflection under the influence of dead and live load (LC2)

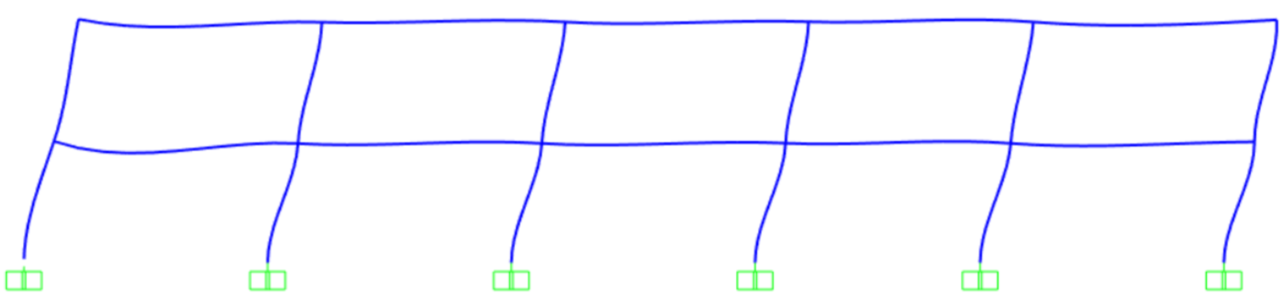


Figure 3. 7: Deflection under the influence of seismic, live, and dead load (LC5)

Chapter 4: Precast Concrete Slab System

Precast concrete is fabricated separately in the manufacturing plant and then installed on the site. Precast members can be either reinforced or prestressed concrete. Prestressed concrete is the formwork of concrete in which high-stress compressive force is induced due to steel tendons prior to exposure to service loads. The prestressing generates a compressive force that helps to counteract the tensile force after exposure to service loads. The precast member is usually used for architectural elements i.e. to carry the structural load or non-structural portion of the building. It is commonly used for floors, columns, walls, or roof components. Since it can be pre-casted away from the site it helps in potential savings in time and economy.

In this section, the one-way solid slab is replaced with hollow-core precast concrete slab. The hollow-core precast concrete slabs are analyzed and the loading is determined. The hollow-core precast concrete slabs are lighter than the solid reinforced concrete slab. The main purpose for replacing the slabs was to analyze the change in loadings and to evaluate the results when lighter slab systems are used.

In terms of loading, the superimposed dead load, live load, rain load, and snow load remain constant. However, the self-weight of the slab fluctuates which might cause a difference in overall dead load and seismic loadings for the precast concrete slabs.

4.1 Estimating the load

As the live load, superimposed dead load, rain load and snow load remain the same, the precast concrete slab is analyzed for dead load and seismic loadings only.

Estimating Dead Load

The hollow core slab was selected using the PCI handbook [16]. The hollow core slab 4HC6+2 of 87-S is selected for the slab as shown in Figure 4.1. The slab with 2-inch toppings is selected as it provides a finished floor process and insulation.

3.6 Hollow-Core Load Tables

Strand Pattern Designation
76-S

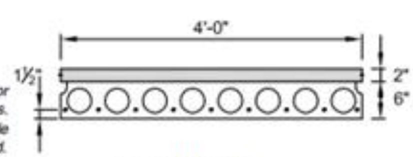
- S = straight
- Diameter of strand in 16ths
- Number of strand (7)

Safe loads shown include dead load of 10 lb/ft² for untopped members and 15 lb/ft² for topped members. Remainder is live load. Long-time cambers include superimposed dead load but do not include live load.

Capacity of sections of other configurations are similar. For precise values, see local hollow-core manufacturer.

Key
290– Safe superimposed service load, lb/ft²
0.1 – Estimated camber at erection, in.
0.2 – Estimated long-time camber, in.

4'-0" × 6"
Normalweight Concrete



f'_c = 5000 psi

f_{pu} = 270,000 psi

Section Properties

	No Topping	2 in. topping
A =	187 in.²	-
I =	763 in.⁴	1640 in.⁴
y_b =	3.00 in.	4.14 in.
y_t =	3.00 in.	3.86 in.
S_b =	254 in.³	396 in.³
S_t =	254 in.³	425 in.³
wt =	195 lb/ft	295 lb/ft
DL =	49 lb/ft²	74 lb/ft²
V/S =	1.73 in.	

4HC6 + 2

Table of safe superimposed service load, lb/ft², and cambers, in. — **2 in. Normalweight Topping**

Strand designation code	Span, ft 12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
66-S	333	300	272	248	227	210	182	158	136	113	93	75	59	46	34				
	0.2	0.2	0.2	0.2	0.2	02	0.2	0.2	0.2	0.2	0.1	0.1	0.0	–0.1	–0.2				
	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.0	–0.1	–0.2	–0.3	–0.5	–0.7	–0.9	–1.2				
76-S		357	324	296	272	248	216	188	163	137	115	95	78	63	50	38	27		
		0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.1	0.1	–0.0	–0.1	–0.3		
		0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.0	–0.2	–0.3	–0.5	–0.7	–0.9	–1.2	–1.5		
96-S			418	384	353	319	279	245	216	186	160	137	116	98	82	68	55	43	33
			0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.4	0.3	0.3	0.1	0.0	–0.1
			0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.3	0.2	0.1	–0.1	–0.3	–0.5	–0.7	–1.0	–1.4	–1.7
87-S			422	388	359	332	309	288	258	224	195	169	147	127	109	94	80	67	55
			0.5	0.5	0.6	0.6	0.7	0.7	0.7	0.7	0.8	0.8	0.7	0.7	0.7	0.6	0.5	0.4	0.3
			0.5	0.5	0.5	0.6	0.6	0.6	0.5	0.5	0.4	0.4	0.2	0.1	–0.1	–0.3	–0.5	–0.8	–1.2
97-S			473	433	400	371	346	323	288	251	219	192	168	146	127	110	95	82	70
			0.5	0.6	0.7	0.7	0.8	0.8	0.9	0.9	0.9	0.9	1.0	0.9	0.9	0.9	0.8	0.7	0.6
			0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.5	0.4	0.2	0.0	–0.2	–0.5	–0.8

Strength is based on strain compatibility; bottom tension is limited to $7.5\sqrt{f'_c}$; see pages 3–8 through 3–11 for explanation.
See item 3, note 4, Section 3.3.2 for explanation of vertical line.

Figure 4. 1: Precast Concrete Hollow Slab [16]

Table 4. 1: Self-weight calculation for prestressed concrete.

Dead Load Calculation		
wt. of concrete	**slab thickness**	**slab self wt**
pcf	in (assume)	psf
150	8	74

The seismic loading for the moment frame in the precast concrete slab is shown in Table 4.2.

Table 4. 2: Distribution of shear over the height of structure for precast concrete [8]

Floor	h_x(ft)	w_x (k/ft)	$w_x h_x$ (kft)	C_{vx}	F_x (k)	f_x (k/ft)
First	12	752.1	9025.2	0.48	83.78	0.70
Roof	24	402.5	9659.52	0.52	89.67	0.75

As shown in the Table 4.2 the seismic loading is significantly reduced for the precast concrete slabs as compared to reinforced concrete slab systems.

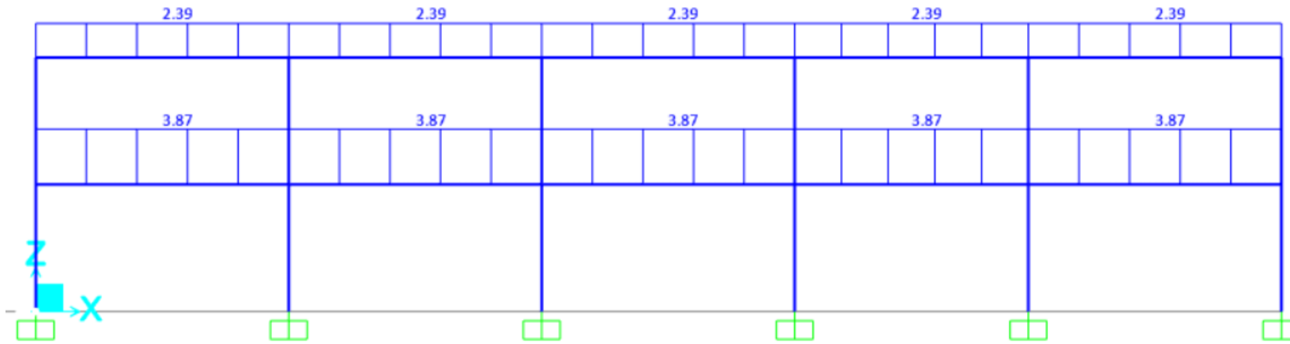


Figure 4. 2: Dead Load for the hollow core slab

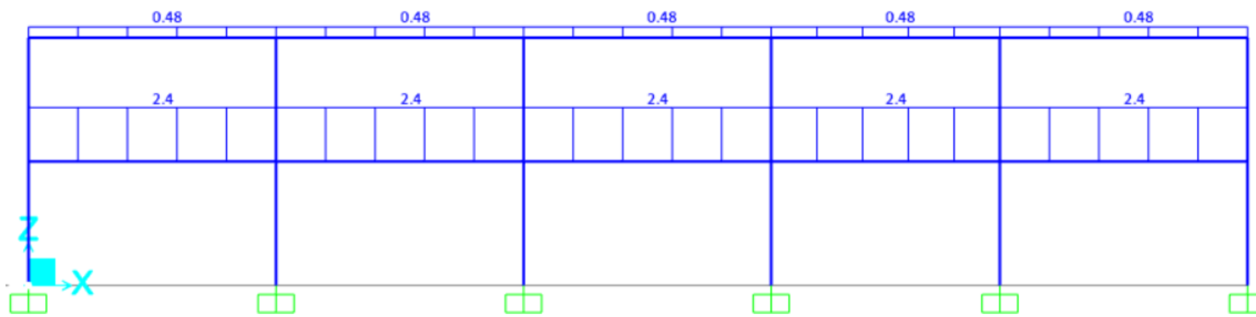


Figure 4. 3: Live Load for the hollow core slab

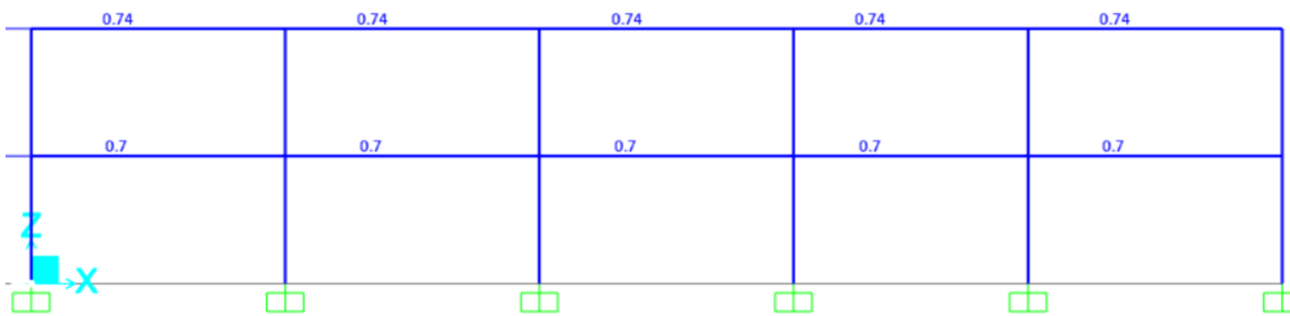


Figure 4. 4: Seismic Load for the hollow core slab

5. RESULTS AND DISCUSSION

In this section, the outcomes of the results from different calculations are analyzed and interpreted. SAP 2000 analyses were performed with the provided loadings and the results are shown in APPENDIX B.

Table 4. 3: Comparison of maximum shear and bending moment in various cases.

	RC	RC with seismic	PC with seismic
Shear (k)	138.73	134.43	103.74
Positive Bending moment (kft)	378.17	321.69	250.60
Negative Bending moment (kft)	-589.23	-656.00	-511.40

Table 4.3 represents the outcome of maximum values for shear and bending moment. The shear value for the reinforced concrete is within the same range and independent of the seismic loading. In a hollow-core slab, the shear is decreased significantly.

On the other hand, the negative moment is maximum when the seismic loading is considered. The negative moment increases by 11% in the seismic loading reinforced concrete slab case as compared to the case when seismic loading is not considered. Although the seismic loading is considered for the hollow core slab, the negative moment is still below the reinforced concrete slab.

Besides the positive moment is within the same range for the reinforced concrete despite seismic loading considered. In this case, also the moment is reduced in the case of prestressed concrete slab system as compared to reinforced concrete system.

To determine the efficiency of the hollow core slab versus reinforced concrete slab, the overall loading is determined as shown in Table 4.4. The load was significantly reduced in the case of precast concrete as compared to reinforced concrete.

Table 4. 4: Reduction in the load

Structural System	Load for the frame (k)	Overall Loadings (k)
Reinforced concrete	1592	11166
Hollow-core slab	1155	5850
Load reduction	27%	48%

5.1 Beam Analysis

The beam on the first floor B3 was further analyzed to verify if the beam size and the reinforcement were satisfactory. All the calculations are shown in Appendix Figure A.11 to A.14. To determine the bar size, f'_c is considered as 4000 psi and f_y is considered as 60000 psi. Table 4.5 demonstrates the beam size and the bars for the beam.

Table 4. 5: Analysis of Beam B3

Beam B3	**Beam dimensions**	**Number of bars**
Reinforced concrete	22”×30”	6 # 9
Reinforced concrete with seismic	22”×30”	7 # 9
Hollow core slab	22”×28”	6 # 9

The steps that are analyzed to determine the beam dimensions are provided below [13]:

- The preliminary dimension of the beam is determined as 22”×30”
- The bending moment (M_u) value is determined from the SAP 2000 analysis.
- Then, $\frac{M_u}{\emptyset bd^2}$ is determined and from that value, the ρ is determined from the Table shown in Figure C.2.
- Then the required area is determined using $A_s = \rho bd$. Then the required bar area is determined using Figure C.3
- Also, the beam is check for the tension controlled. $\varepsilon_t \geq 0.005$

As demonstrated in Table 4.4, the reinforced concrete with seismic and reinforced concrete beam dimensions are the same but the seismic design requires extra bars in the beam. Also, if a hollow core is considered then the beam dimensions can be reduced as well.

All the data demonstrates that the seismic load should be considered while designing the building. Although, the difference for the moment is not high for a 2-story low-rise building seismic design should be considered for the high-rise building. Also, the seismic loading of such a moderate frequency impacted the moment significantly. However, in the case of greater frequency, the buildings can face catastrophic events if not considered the seismic loadings.

In the case of hollow core slab, the loadings have significantly reduced which results in a more efficient design. Because of the lighter weight than one-way solid slab, the design and loading in the building are significantly improved. This suggests that the precast hollow concrete slab is more appropriate for this project than the one-way solid slab.

5.2 Cost Analysis

Cost analysis between the hollow core slab and one-way slab is performed to compare their costs [14]. The cost of precast slabs is slightly more expensive than the reinforced concrete as shown in Table 4.6.

Table 4. 6: Cost Analysis for hollow core slab and precast slab

Structural system	Area of each floor (ft^2)	Total area (ft^2)	Estimated Cost $/ft^2$	Total Cost ($) per floor	Total Cost ($)
Reinforced Concrete (one way solid slab)	11760	47040	28	329280	1317120
Precast slab (hollow core slab)	11760	47040	29	341040	1364160

The flooring cost is not considered in the cost analysis above. HC slab doesn't require flooring because it has a 2" topping which acts as the floor finish and insulator. The HC slab can be exposed, left unpainted, and cleaned easily [25]. However, the solid slab requires flooring, paint and is harder to clean as compared to the hollow core slab. If the flooring and paint cost is considered then the total cost of the solid slab will be increased. In the case of a hollow core slab, each beam dimension is decreased by 2" so, a slightly less concrete is required which can also decrease the cost of the hollow core slab system.

The precast slab is design-build efficient i.e. it can be constructed off-site while the other designs are being developed. Because of this, it can be constructed in all weather and the project is completed at the scheduled time and earlier than the one-way solid slab [6]. If the project is completed earlier then the owner can lease the property earlier and gain profit than the one-way solid slab system. So, in the long-term hollow core slab is more beneficial than the one-way solid slab floor systems.

Besides hollow core slab requires less labor and it can be erected smoothly so it is safer in construction. It can also absorb sound, making it ideal slab systems for this commercial building project. Although the cost of the precast slab is more expensive than the reinforced concrete slabs, all these advantages of precast outweigh the cost benefits for the reinforced concrete slabs.

6. SUMMARY AND CONCLUSIONS

The objective of the thesis to analyze the seismic effects and compare two slab floor systems to select the efficient slab flooring was accomplished. The loadings on the beam were superior when seismic loadings were considered as compared to the case with only gravitational loadings. The positive moment difference was insignificant but the negative moments were greater. This might be because only lateral seismic loadings were applied inducing high value for moments at the joints.

Although the frequency of the earthquake was small, it resulted in an 11% increase for the negative moment. The frequency of earthquake occurrence fluctuates from time to time and there is no specific value so, it is always advantageous to consider seismic loadings while designing. Besides, if it is a high-rise building then it will have a larger value for seismic design base shear resulting in greater seismic loadings.

The precast slab significantly increased loadings efficiency in the building and proved to be beneficial than the reinforced one-way solid slab floor systems. Besides, using the PC slabs have many advantages over reinforced concrete. Although the cost of the precast slab is slightly expensive, it is reasonable while looking at long-term effects. It can also be installed conveniently and requires less labor than the reinforced concrete floor systems.

7. RECOMMENDATION

The analysis procedure used in the seismic analysis is the equivalent lateral force (ELF) procedure. But there are other different procedures like simplified design procedures and dynamic analysis procedures. So the other procedure must also be analyzed and the critical load must be selected.

The seismic loading can also be designed by looking at the previous earthquake frequency data in Oxford. Only ASCE-7 Hazard Tool was used to analyze the earthquake loadings. If this work is to be reiterated then non-linear seismic loadings cases should also be considered following the past earthquake frequency data.

The beam and slabs are only designed in this thesis but columns are significantly affected by the seismic loading. So, the column must be analyzed as well. Also, all the analysis is performed only for the 2-D structure but it would give accurate results if the analysis is performed in 3-D. Besides, stairs and elevator loadings should be considered to get precise results.

The ordinary reinforced concrete moment frame can be replaced by other seismic resisting systems like shear walls. Also, the design can be made more economical by replacing the concrete walls with precast walls.

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APPENDICES

APPENDIX A- Sample Calculations

Roof					
Element		**Area** ft^2	**Height** ft	**Volume** ft^3	**Load** kips
Slab		2880	1.00	2880	432
Superimposed DL		2880	1.00	2880	20.2
Beam	B8	3.00	120	360	54
				Total DL	**506.2**
Live Load		2880	1.00	2880	57.6
Environmental Load		2880	1.00	2880	57.6
				Total wt	**621.4**

First floor					
Element		**Area** ft^2	**Height** ft	**Volume** ft^3	**Load** kips
Slab		2880	1.00	2880	432
Superimposed DL		2880	1	2880	168.5
Beam	B3	4.583	120	550	82.5
				Total DL	**683.0**
Live Load		2880	1.00	2880	288
				Total wt	**971.0**
Weight of struture			**1592 kips**		

Figure A. 1: Calculation for the weight of the structure for RC slab floor system

Dead load for the Beam B3						lb/ft
	Weight from slab	3.6	k/ft	LC1	1.4D	7.97
	Superimposed	1.4	k/ft	LC2	1.2D+ 1.6L +0.5(Lr or S or R)	**10.67**
	Beam self wt	0.69	k/ft	LC3	1.2D+1.6(Lr or S or R) +(L or 0.5W)	9.23
	Total DL	**5.69**	**k/ft**	LC4	1.2D +W+L+0.5(Lr or S or R)	9.23
				LC5	1.2D + 1.0E + L + 0.2S	9.23
Live Load		**2.4**	**k/ft**	LC6	0.9D+1.0W	5.12
				LC7	0.9D+E	6.00

Figure A. 2: LRFD combinations for Beam B3 for RC system without seismic loading

Dead load for the Beam B8					psf
Weight from slab	3.6	k/ft	LC1	1.4D	5.91
Superimposed	0.2	k/ft	LC2	1.2D+ 1.6L +0.5(Lr or S or R)	**6.07**
Beam self wt	0.45	k/ft	LC3	1.2D+1.6(Lr or S or R) +(L or 0.5W)	5.83
Total DL	**4.22**	**k/ft**	LC4	1.2D +W+L+0.5(Lr or S or R)	5.78
			LC5	1.2D + 1.0E + L + 0.2S	5.64
Live load	**0.48**	**k/ft**	LC6	0.9D+1.0W	3.80
			LC7	0.9D+E	1.55

Figure A. 3: LRFD combinations for Beam B8 for RC system without seismic loading

	[USGS website]			$S_{DS} = \frac{2}{3} F_a S_s$	$S_{D1} = \frac{2}{3} F_v S_1$				structure		$V=C_sW$
S_S	S_1	F_a	F_v	S_{DS}	S_{D1}	R	Ie	Cs	height	weight (W)	Shear (V)
									ft	k	k
0.416	0.179	1.3	1.5	0.361	0.179	3	1.25	0.15	24	1592	239

Floor	h_x	w_x	$w_x h_x$	**Cvx**	**Fx**	**Fx**
	ft	**kft**	**kft**		**k**	**k/ft**
First	12	971.0	11652	0.44	104.92	**0.87**
Roof	24	621.4	14913	0.56	134.28	**1.12**
		$\Sigma w_i h_i$	26564.4			

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k}$$

Figure A. 4: Seismic Load Calculation for RC slab floor system

For seismic combination for B3		
LC1	$(1.2+0.2S_{DS})D+f_1L+f_2S+\rho Q_E$	10.51
LC2	$(0.9-0.2S_{DS})D+\rho Q_E$	5.59

Figure A. 5: LRFD combinations for Beam B3 for RC system with seismic loading

For seismic combination for B8		
LC1	$(1.2+0.2S_{DS})D+f_1L+f_2S+\rho Q_E$	7.44
LC2	$(0.9-0.2S_{DS})D+\rho Q_E$	4.61

Figure A. 6: LRFD combinations for Beam B8 for RC system with seismic loading

Roof

Element		Area	Height	Volume	Load
		ft^2	ft	ft^3	kips
Slab		2880	0.67	1920	213.12
Superimposed DL		2880	0.67	1920	20.2
Beam	B8	3.00	120	360	54
				Total DL	**287.3**
Live Load		2880	0.67	1920	57.6
Environmental Load		2880	0.67	1920	57.6
				Total wt	**402.5**

First floor

Element		Area	Height	Volume	Load
		ft^2	ft	ft^3	kips
Slab		2880	0.67	1920	213.12
Superimposed DL		2880	0.67	1920	168.5
Beam	B3	4.583	120	550	82.5
				Total DL	**464.1**
Live Load		2880	0.67	1920	288
			Total wt		**752.1**

Weight of struture **1154.6 kips**

Figure A. 7: Calculation for the weight of the structure for PC slab floor system

		lb/ft
LC1	1.4D	5.41
LC2	1.2D+ 1.6L +0.5(Lr or S or R)	**8.48**
LC3	1.2D+1.6(Lr or S or R) +(L or 0.5W)	7.04
LC4	1.2D +W+L+0.5(Lr or S or R)	7.04
LC5	1.2D + 1.0E + L + 0.2S	7.04
LC6	0.9D+1.0W	3.48
LC7	0.9D+E	4.18
For seismic combination for B3		
LC1	$(1.2+0.2S_{DS})D+f_1L+f_2S+\rho Q_E$	8.02
LC2	$(0.9-0.2S_{DS})D+\rho Q_E$	3.90

Figure A. 8: LRFD load combinations for Beam B3 for PC structural system

		psf
LC1	1.4D	3.35
LC2	1.2D+ 1.6L +0.5(Lr or S or R)	**3.88**
LC3	1.2D+1.6(Lr or S or R) +(L or 0.5W)	3.64
LC4	1.2D +W+L+0.5(Lr or S or R)	3.59
LC5	1.2D + 1.0E + L + 0.2S	3.45
LC6	0.9D+1.0W	2.15
LC7	0.9D+E	1.18
For seismic combination for B8		
LC1	$(1.2+0.2S_{DS})D+f_1L+f_2S+\rho Q_E$	4.75
LC2	$(0.9-0.2S_{DS})D+\rho Q_E$	2.73

Figure A. 9: LRFD load combinations for Beam B8 for PC structural system

	[USGS website]			$S_{DS} = \frac{2}{3} F_a S_s$	$S_{D1} = \frac{2}{3} F_v S_1$				structure		Cs*W
S_S	S_1	F_a	F_v	S_{DS}	S_{D1}	R	Ie	Cs	height	weight (W)	Shear (V)
									ft	k	k
0.416	0.179	1.3	1.5	0.361	0.179	3	1.25	0.15	24	1155	173

Floor	h_x	w_x	$w_x h_x$	Cvx	Fx	Fx
	ft	k	kft		k	k/ft
First	12	752.1	9025.2	0.48	83.78	0.70
Roof	24	402.5	9659.52	0.52	89.67	0.75
		$\Sigma w_i h_i$	18684.72			

$$C_{vx} = \frac{w_x h_x^k}{\sum_{i=1}^{n} w_i h_i^k}$$

Figure A. 10: Seismic Load Calculation for PC slab floor system

	Building A Beam Design B3										
	width (b)	**depth (d)**	**Φ**	**fy**	**fc**		**height (h)**	**β1**			
	in	in		ksi	ksi	psi	in	since f'c =4ksi			
	22	27.5	0.9	60	4	4000	30	0.85			
	For B3 without seismic										
For Reinforcement											
	CA3		CB3		CC3		CD3		CE3		CF3
Mu	-350.13	324.23	-589.23	304.33	-546.52	318.49	-522	245.7	-496.72	378.17	-285.66
$Mu/\phi bd^2$	-0.2806	0.259838718	0.47221	0.243891	0.437982	0.255239	0.418332	0.196905	0.398073	0.303066	-0.22893
	-280.595	259.8387178	472.2104	243.8908	437.9825	255.2387	418.3321	196.9046	398.0726	303.0664	-228.929
ρ	0.0048	0.0048	0.0090	0.0045	0.0083	0.0047	0.0079	0.0036	0.0075	0.0056	0.0033
ρ_{used}	0.0048	0.0048	0.0090	0.0045	0.0083	0.0047	0.0079	0.0036	0.0075	0.0056	0.0033
As (in^2)	2.89	2.90	5.47	2.71	5.04	2.84	4.80	2.17	4.55	3.41	2.00
Checking if beam is tension controlled or not											
a (in)	2.32	2.32	4.39	2.18	4.04	2.28	3.85	1.74	3.65	2.73	1.60
c	2.73	2.73	5.16	2.56	4.76	2.68	4.53	2.05	4.29	3.21	1.88
ε_t	0.027	0.027	0.013	0.029	0.014	0.028	0.015	0.037	0.016	0.023	0.041
	Check εt ≥ 0.005 so ϕ=0.9										
Reinforce	6 #9	6 #9	6 #9	6 #9	6 #9	6 #9	6 #9	6 #9	6 #9	6 #9	6 #9
		flexural									

Figure A. 11: Design of Beam B3 only on gravitational load for RC slab.

For B3 with seismic											
	CA3		CB3		CC3		CD3		CE3		CF3
Mu	-87.38	321.69	-656	234.87	-647.68	243.2	-612.81	188.66	-613.16	273.77	-535.48
$Mu/\phi bd^2$	-0.070026546	0.257803	0.52572	0.188225	0.519052	0.194901	0.491107	0.151193	0.491388	0.2194	-0.42913
	-70.02654646	257.8032	525.72	188.2254	519.0523	194.9011	491.1074	151.1926	491.3879	219.3999	-429.135
ρ	0.0033	0.0048	0.0102	0.0034	0.0100	0.0036	0.0094	0.0027	0.0094	0.0040	0.0033
ρ_{used}	0.0033	0.0048	0.0102	0.0034	0.0100	0.0036	0.0094	0.0033	0.0094	0.0040	0.0033
As (in^2)	2.00	2.87	6.15	2.07	6.06	2.15	5.71	2.00	5.71	2.43	2.00
Checking if beam is tension controlled or not											
a (in)	1.60	2.31	4.93	1.66	4.86	1.73	4.58	1.60	4.58	1.95	1.60
c	1.88	2.71	5.80	1.96	5.72	2.03	5.39	1.88	5.39	2.29	1.88
ε_t	0.041	0.027	0.011	0.039	0.011	0.038	0.012	0.041	0.012	0.033	0.041
	Check εt ≥ 0.005 so ϕ=0.9										
Reinforce	6 #8	7 #7	7 #7	7 #7	7 #7	7 #7	7 #7	7 #7	7 #7	7 #7	7 #7
		flexural									

Figure A. 12: Design of Beam B3 in presence of seismic load for RC slab.

Building A Beam Design B3

	width (b)	depth (d)	Φ	fy	fc		height (h)	β1			
	in	in		ksi	ksi	psi	in	since f'c =4ksi			
	22	25.5	0.9	60	4	4000	28	0.85			
	For B3 with seismic										
For Reinforcement											
	CA3		CB3		CC3		CD3		CE3		CF3
Mu	-50.36	250.6	-511.4	180.79	-506	187.94	-478.33	145.45	-481.43	210.9	-420.69
$Mu/\phi bd^2$	-0.04694	0.23357	0.476647	0.168504	0.471613	0.175168	0.445824	0.135566	0.448713	0.196568	-0.3921
	-46.9377	233.5698	476.6465	168.504	471.6135	175.1681	445.8239	135.5656	448.7132	196.5678	-392.101
ρ	0.0008	0.0043	0.0091	0.0031	0.0090	0.0032	0.0085	0.0024	0.0086	0.0036	0.0033
ρ_{used}	0.0033	0.0043	0.0091	0.0033	0.0090	0.0033	0.0085	0.0033	0.0086	0.0036	0.0033
As (in^2)	1.85	2.41	5.12	1.85	5.06	1.85	4.76	1.85	4.80	2.01	1.85
Checking if beam is tension controlled or not											
a (in)	1.49	1.93	4.11	1.49	4.06	1.49	3.82	1.49	3.85	1.61	1.49
c	1.75	2.27	4.83	1.75	4.78	1.75	4.50	1.75	4.53	1.90	1.75
ε_t	0.041	0.031	0.013	0.041	0.013	0.041	0.014	0.041	0.014	0.037	0.041
	Check εt ≥ 0.005 so ϕ=0.9										

Figure A. 13: Design of Beam B3 considering seismic load for PC slab.

Reinforced concete					
Element		**Area**	**Height**	**Volume**	**Load**
Component	**Number**	ft^2	ft	ft^3	kips
Slab	2	11760	1.00	11760	3528
Superimpos	First	11760	1.00		688.0
	Roof	11760	1.00		82.32
Beam B3	5	4.431	120	531.7	398.75
Beam B8	5	2.917	120	350	262.5
				Total DL	**4877.2**
Live Load	First	11760	1.00		1176
	Roof	11760	1		235.2
				Total LL	**6053.2**
Env. Load	Roof	11760	1		235.2
				Total loac	**11165.6**

Figure A. 14: Total weight of building for RC slab floor systems

Prestressed concete					
Element		**Area**	**Height**	**Volume**	**Load**
Component	**Number**	ft^2	ft	ft^3	kips
Slab	2	11760	0.67		870.24
Superimposed	First	11760	0.67		688.0
	Roof	11760	0.67		82.3
Beam B3	5	4.431	120	531.7	398.75
Beam B8	5	2.917	120	350	262.5
				Total DL	**2219.5**
Live Load	First	11760	0.67		1176
	Roof	11760	0.67		235.2
				Total LL	**3395.5**
Env. Load	Roof	11760	0.67		235.2
				Total load	**5850.1**

Figure A. 15: Total weight of building for RC slab floor systems

APPENDIX B- SAP 2000 Results

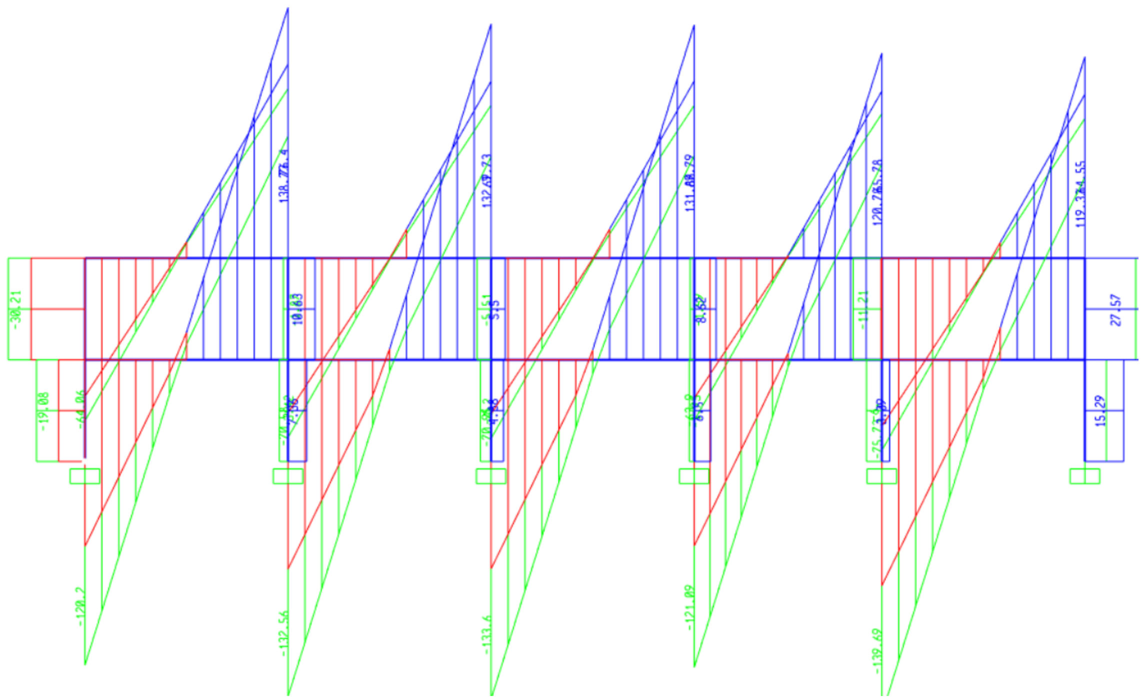

Figure B. 1: Shear diagram for RC without seismic loading

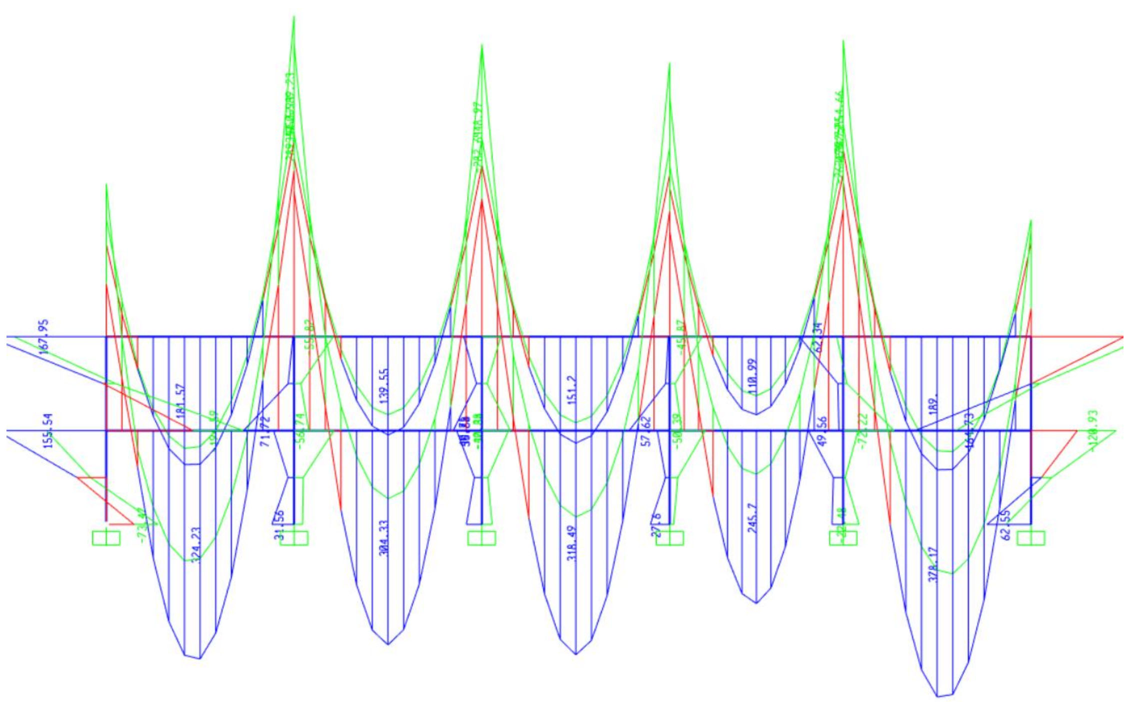

Figure B. 2: Moment diagram for RC without seismic loading

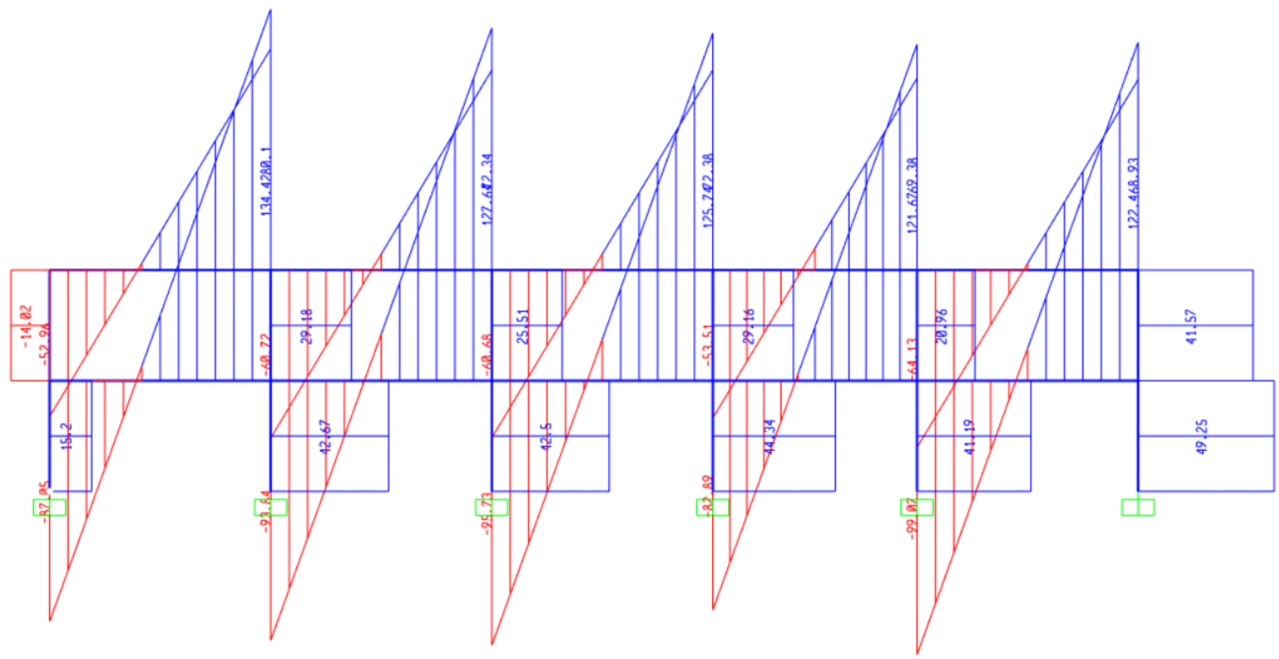

Figure B. 3: Shear diagram for RC with seismic loading

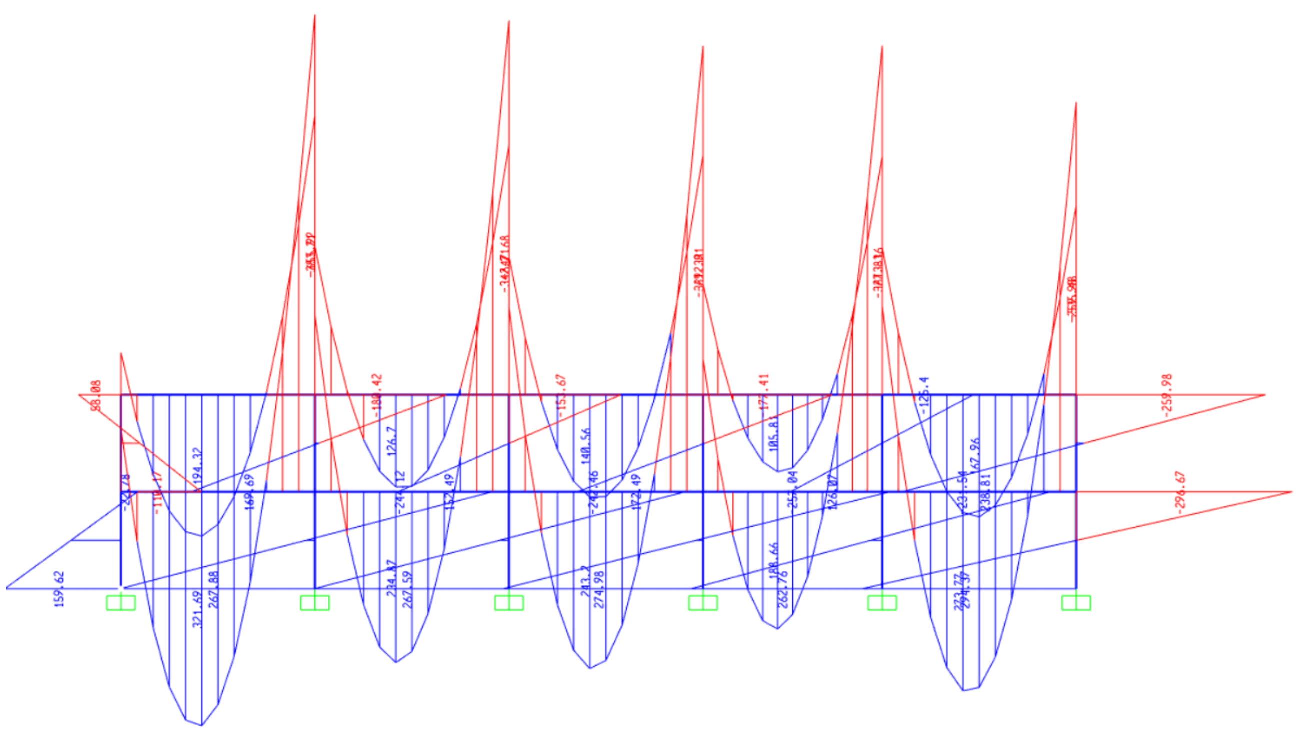

Figure B. 4: Moment diagram for RC with seismic loading

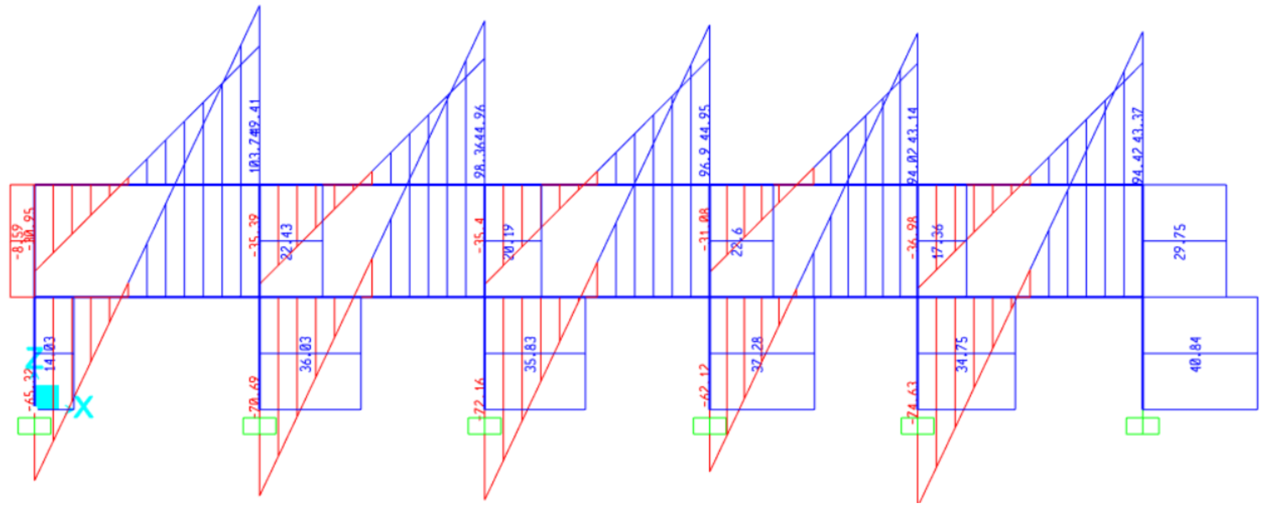

Figure B. 5: Shear diagram for PC with seismic loading

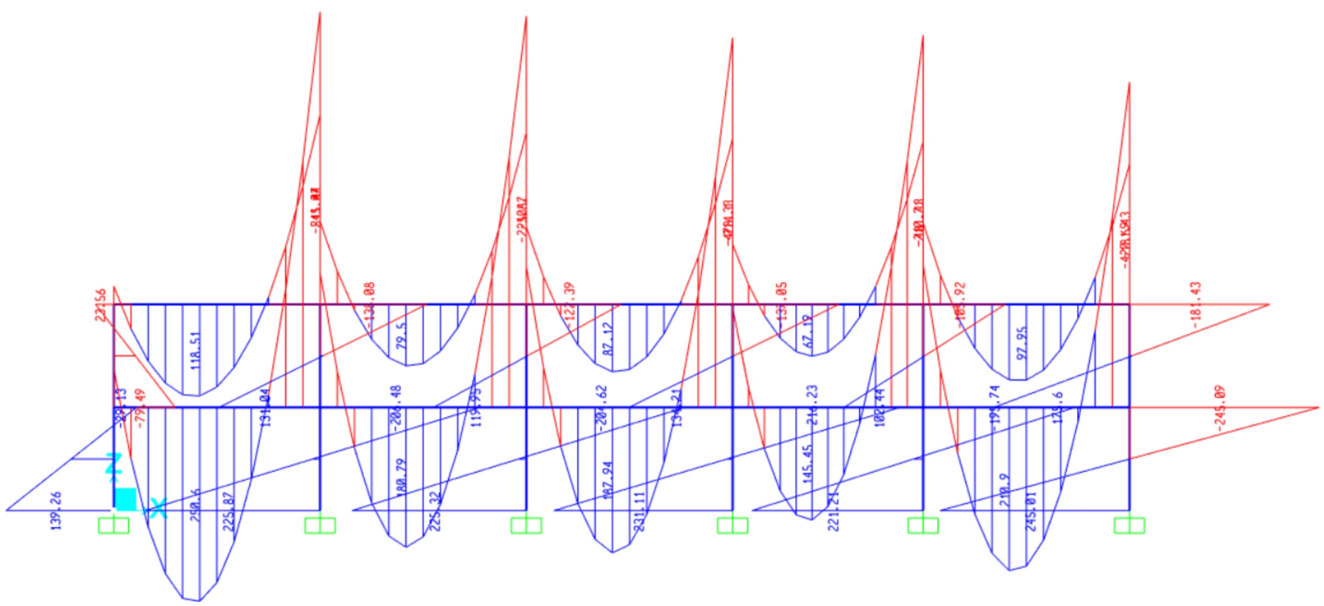

Figure B. 6: Moment diagram for PC with seismic loading

APPENDIX C - DATA

Table 11.4-1 Site Coefficient, F_a

Site Class	Mapped Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameter at Short Period				
	$S_S \le 0.25$	$S_S = 0.5$	$S_S = 0.75$	$S_S = 1.0$	$S_S \ge 1.25$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	See Section 11.4.7				

Note: Use straight-line interpolation for intermediate values of S_S.

Table 11.4-2 Site Coefficient, F_v

Site Class	Mapped Risk-Targeted Maximum Considered Earthquake (MCE_R) Spectral Response Acceleration Parameter at 1-s Period				
	$S_1 \le 0.1$	$S_1 = 0.2$	$S_1 = 0.3$	$S_1 = 0.4$	$S_1 \ge 0.5$
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F	See Section 11.4.7				

Note: Use straight-line interpolation for intermediate values of S_1.

Figure C. 1: ASCE-7 Table 11.4.1 and 11.4.2

TABLE A.13 f_y = 60,000 psi; f'_c = 4000 psi—U.S. Customary Units

	ρ	$\frac{M_u}{\phi bd^2}$	ρ	$\frac{M_u}{\phi bd^2}$	ρ	$\frac{M_u}{\phi bd^2}$	ρ	$\frac{M_u}{\phi bd^2}$
ρ_{min} for	0.0018	106.3	0.0059	335.5	0.0100	546.9	0.0141	740.4
temp. and	0.0019	112.1	0.0060	340.9	0.0101	551.8	0.0142	744.9
shrinkage	0.0020	117.1	0.0061	346.2	0.0102	556.7	0.0143	749.4
	0.0021	123.7	0.0062	351.6	0.0103	561.7	0.0144	753.9
	0.0022	129.4	0.0063	356.9	0.0104	566.6	0.0145	758.3
	0.0023	135.2	0.0064	362.2	0.0105	571.5	0.0146	762.8
	0.0024	141.0	0.0065	367.6	0.0106	576.3	0.0147	767.2
	0.0025	146.7	0.0066	372.9	0.0107	581.2	0.0148	771.7
	0.0026	152.4	0.0067	378.2	0.0108	586.1	0.0149	776.1
	0.0027	158.1	0.0068	383.4	0.0109	590.9	0.0150	780.5
	0.0028	163.8	0.0069	388.7	0.0110	595.7	0.0151	784.9
	0.0029	169.5	0.0070	394.0	0.0111	600.6	0.0152	789.3
	0.0030	175.2	0.0071	399.2	0.0112	605.4	0.0153	793.7
	0.0031	180.9	0.0072	404.5	0.0113	610.2	0.0154	798.1
	0.0032	186.6	0.0073	409.7	0.0114	615.0	0.0155	802.4
ρ_{min} for	0.0033	192.2	0.0074	414.9	0.0115	619.8	0.0156	806.8
flexure	0.0034	197.9	0.0075	420.1	0.0116	624.5	0.0157	811.1
	0.0035	203.5	0.0076	425.3	0.0117	629.3	0.0158	815.4
	0.0036	209.1	0.0077	430.5	0.0118	634.1	0.0159	819.7
	0.0037	214.7	0.0078	435.7	0.0119	638.8	0.0160	824.1
	0.0038	220.3	0.0079	440.9	0.0120	643.5	0.0161	828.3
	0.0039	225.9	0.0080	446.0	0.0121	648.2	0.0162	832.6
	0.0040	231.5	0.0081	451.2	0.0122	653.0	0.0163	836.9
	0.0041	237.1	0.0082	456.3	0.0123	657.7	0.0164	841.2
	0.0042	242.6	0.0083	461.4	0.0124	662.3	0.0165	845.4
	0.0043	248.2	0.0084	466.5	0.0125	667.0	0.0166	849.7
	0.0044	253.7	0.0085	471.6	0.0126	671.7	0.0167	853.9
	0.0045	259.2	0.0086	476.7	0.0127	676.3	0.0168	858.1
	0.0046	264.8	0.0087	481.8	0.0128	681.0	0.0169	862.3
	0.0047	270.3	0.0088	486.9	0.0129	685.6	0.0170	866.5
	0.0048	275.8	0.0089	491.9	0.0130	690.3	0.0171	870.7
	0.0049	281.2	0.0090	497.0	0.0131	694.9	0.0172	874.9
	0.0050	286.7	0.0091	502.0	0.0132	699.5	0.0173	879.1
	0.0051	292.2	0.0092	507.1	0.0133	704.1	0.0174	883.2
	0.0052	297.6	0.0093	512.1	0.0134	708.6	0.0175	887.4
	0.0053	303.1	0.0094	517.1	0.0135	713.2	0.0176	891.5
	0.0054	308.5	0.0095	522.1	0.0136	717.8	0.0177	895.6
	0.0055	313.9	0.0096	527.1	0.0137	722.3	0.0178	899.7
	0.0056	319.3	0.0097	532.0	0.0138	726.9	0.0179	903.9
	0.0057	324.7	0.0098	537.0	0.0139	731.4	0.0180	907.9
	0.0058	330.1	0.0099	542.0	0.0140	735.9	0.0181	912.0

Figure C. 2: Table to determine the concrete steel ratio ρ

TABLE A.4 Area of Groups of Bars, in.^{2}

Number of Bars	Bar Size Designation										
	#3	#4	#5	#6	#7	#8	#9	#10	#11	#14	#18
2	0.22	0.39	0.61	0.88	1.20	1.57	2.00	2.54	3.12	4.50	8.00
3	0.33	0.59	0.92	1.33	1.80	2.36	3.00	3.81	4.68	6.75	12.00
4	0.44	0.79	1.23	1.77	2.41	3.14	4.00	5.08	6.24	9.00	16.00
5	0.55	0.98	1.53	2.21	3.01	3.93	5.00	6.35	7.80	11.25	20.00
6	0.66	1.18	1.84	2.65	3.61	4.71	6.00	7.62	9.36	13.50	24.00
7	0.77	1.37	2.15	3.09	4.21	5.50	7.00	8.89	10.92	15.75	28.00
8	0.88	1.57	2.45	3.53	4.81	6.28	8.00	10.16	12.48	18.00	32.00
9	0.99	1.77	2.76	3.98	5.41	7.07	9.00	11.43	14.04	20.25	36.00
10	1.10	1.96	3.07	4.42	6.01	7.85	10.00	12.70	15.60	22.50	40.00
11	1.21	2.16	3.37	4.86	6.61	8.64	11.00	13.97	17.16	24.75	44.00
12	1.33	2.36	3.68	5.30	7.22	9.42	12.00	15.24	18.72	27.00	48.00
13	1.44	2.55	3.99	5.74	7.82	10.21	13.00	16.51	20.28	29.25	52.00
14	1.55	2.75	4.30	6.19	8.42	11.00	14.00	17.78	21.84	31.50	56.00
15	1.66	2.95	4.60	6.63	9.02	11.78	15.00	19.05	23.40	33.75	60.00
16	1.77	3.14	4.91	7.07	9.62	12.57	16.00	20.32	24.96	36.00	64.00
17	1.88	3.34	5.22	7.51	10.22	13.35	17.00	21.59	26.52	38.25	68.00
18	1.99	3.53	5.52	7.95	10.82	14.14	18.00	22.86	28.08	40.50	72.00
19	2.10	3.73	5.83	8.39	11.43	14.92	19.00	24.13	29.64	42.75	76.00
20	2.21	3.93	6.14	8.84	12.03	15.71	20.00	25.40	31.20	45.00	80.00
21	2.32	4.12	6.44	9.28	12.63	16.49	21.00	26.67	32.76	47.25	84.00
22	2.43	4.32	6.75	9.72	13.23	17.28	22.00	27.94	34.32	49.50	88.00

Figure C. 3: Table to determine bar size for the beam B3